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Bridges crossing fault rupture zones: A review

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ABSTRACT

Several earthquakes over the past two decades have demonstrated that bridges crossing fault rupture zones may suffer significant damage due to the combined effects of ground shaking and surface rupture. Although it is widely recommended to avoid building a bridge across a fault, it is not always possible to achieve this objective, especially in regions with a dense network of active faults. This review begins by compiling two databases: one of fault-crossing bridges damaged in past earthquakes and another of bridges crossing potentially active fault rupture zones. The article then continues to review findings of experimental, analytical and numerical studies, and to summarize seismic design provisions and recommendations related to fault-crossing bridges. The review ends with suggestions for future research directions in this area.

1. Introduction

The vulnerability of bridges crossing active fault rupture zones (called "fault-crossing bridges" in this study) has received increasing attention from earthquake engineers over the past two decades. The impetus was provided by the devastating effects of the 1999 M_w 7.4 Kocaeli, 1999 M_w 7.6 Chi-Chi, and 1999 M_w 7.2 Duzce earthquakes on bridge structures traversed by fault rupture zones. Although it is widely recommended to avoid building a bridge across a fault, it is not always possible to achieve this objective, especially in regions with a dense network of active faults.

Active faults that break through the ground surface and have the potential to generate significant fault offset in the event of an earthquake have the capacity to impose a severe combination of ground shaking and surface rupture on fault-crossing bridges. In general, the fault offset may vary from a few centimeters to several meters depending on the earthquake magnitude (e.g., [133]). Similar to non-fault-crossing bridges located in the vicinity of a fault, fault-crossing bridges are subjected to near-fault-pulse-like ground motions affected by forward directivity and permanent translation (fling) (e.g., [81]), but now these ground motions vary across the fault rupture.

According to Slemmons and dePolo [111], there are three main types of surface rupture associated with faulting (Fig. 1): (1) primary rupture, which occurs along the primary fault where most of the seismic energy is released; (2) secondary rupture, which occurs along a secondary (or branch) fault subordinate to the primary fault; and (3) sympathetic (or triggered) rupture, which occurs along another nearby fault that is disturbed by the strain release along the primary fault or the vibratory ground motion. It is noted that a surface fault rupture should not be viewed as a fault line, but rather as a fault zone with a finite width subjected to ground distortion. In this study, a fault-crossing bridge is defined as a bridge structure traversed by a surface fault rupture zone (primary, secondary or sympathetic) passing beneath any portion of the bridge (span, pier, abutment or approach road) (Fig. 1).

This article presents a comprehensive review of case studies, experimental, analytical and numerical investigations, and seismic design codes related to fault-crossing bridges. Two databases – one of fault-crossing bridges damaged in past earthquakes and another of bridges crossing potentially active fault rupture zones – are first compiled based on information provided in the literature. Findings of experimental, analytical and numerical studies of bridges traversed by fault rupture zones are then reviewed. Seismic design provisions and recommendations related to fault-crossing bridges are also summarized. Finally, suggestions for future research directions in this area are proposed. It is noted that a review of studies focusing on other types of structures (e.g., tunnels, dams, pipelines, buildings, etc.) crossing fault rupture zones is beyond the scope of this article.

2. Fault-crossing bridges damaged in past earthquakes

In this section, detailed information about fault-crossing bridges that were damaged in past earthquakes is collected from the literature. This information, which is summarized in Table 1 and discussed next, includes description of bridges, damaging earthquakes, fault crossing conditions and observed damage modes, as well as a comprehensive list

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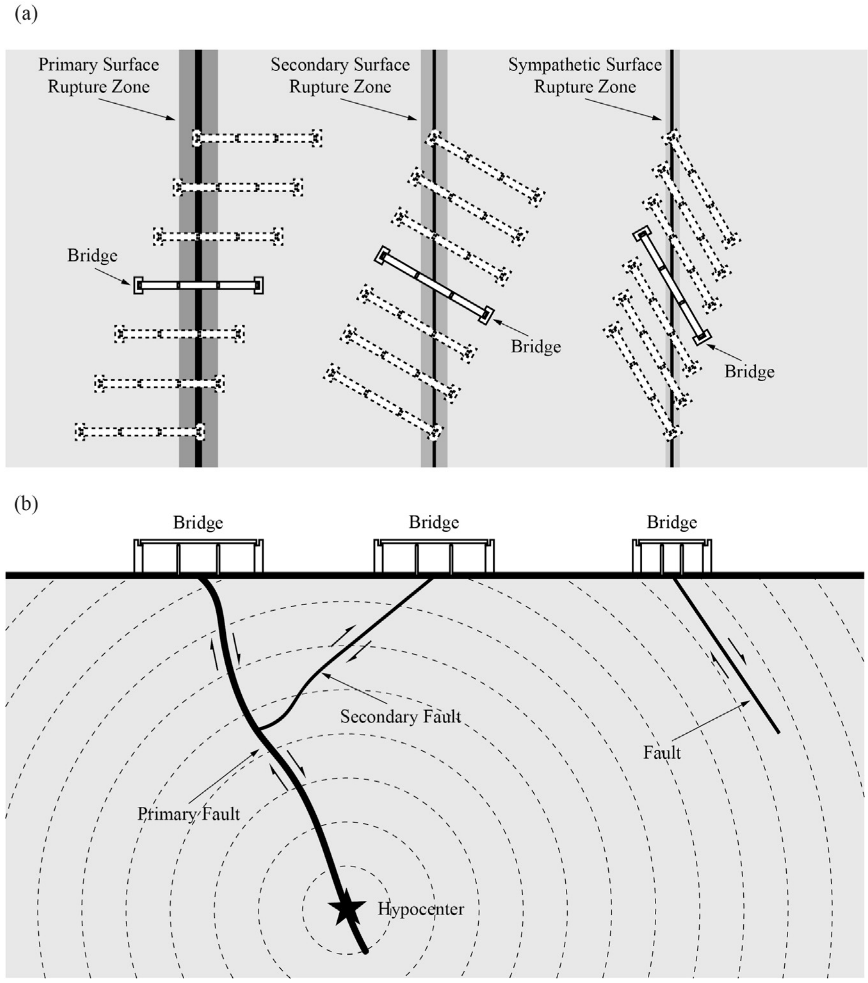

Fig. 1. Schematic of bridges crossing surface fault rupture zones: (a) plan view showing different fault crossing angles and locations; (b) cross-section showing different types of fault rupture (primary, secondary, and sympathetic).

of references.[1] This survey builds upon earlier review studies on this subject conducted by Kawashima [61,62] and Hui [53].

2.1. The 1906 M_w 7.8 San Francisco, California, earthquake

The earliest seismic event associated with damage to bridges induced by surface fault rupture appears to be the 1906 San Francisco earthquake. Specifically, a bridge spanning the Alder Creek northwest from Point Arena was severely damaged when the fault trace passed beneath the bridge near its southwest abutment (Fig. 2a), resulting in the collapse of the Alder Creek Bridge (Fig. 2b) [70]. The horizontal offset along the fault trace, which was greater than the width of the bridge, is also shown in Fig. 2b. A railway bridge spanning the Pajaro River at Chittenden was also damaged due to fault crossing during the 1906 San Francisco earthquake [70,120,10]. The Pajaro River Bridge was a 5-span, curved, steel truss bridge supported by wall-type piers (Fig. 3a and c). The fault trace crossed the bridge beneath pier P3 at an angle of approximately 45° with respect to the bridge axis (Fig. 3c), leading to cracking and displacement of the supporting piers. In addition, as illustrated in Fig. 3b and c, the bridge was dragged from abutment A2 (west abutment) about 1.1 m (3.5 ft), thus lengthening the distance between the abutments. Finally, as mentioned in passing by Lawson et al. [70], two additional bridges – a rough wooden bridge spanning the South Fork of the Gualala River and an old bridge spanning the Russian River – were severely damaged due to fault crossing during the 1906 San Francisco earthquake, but are not discussed further herein due to insufficient information.

2.2. The 1999 M_w 7.4 Kocaeli (Izmit), Turkey, earthquake

The Arifiye Overpass (No. 3 Overpass), located on the Trans-European Motorway near the city of Adapazari, was a 104-m-long, 4-span, skewed, simply-supported, prestressed concrete U-beam bridge (Fig. 4a) on wall-type piers (Fig. 4b) and seat-type abutments (Fig. 4c). Each pier or abutment was supported on cast-in-place reinforced concrete piles (e.g., [56,38,61,62,26,97,138]). The fault rupture zone of the 1999 Kocaeli earthquake passed between abutment A1 (northeast abutment) and pier P1 at an angle of approximately 65° with respect to the longitudinal axis of the bridge (e.g., [126,7]). As shown in Fig. 4d, the northernmost span completely collapsed, whereas the remaining three spans fell off their supports causing 10 fatalities among the passengers of a passing bus [26].

The No. 1 Overpass, located about 1 km east of the Arifiye Overpass, was a 2-span, simply-supported, prestressed concrete bridge on wall-type piers. The bridge was crossed through its southeast abutment by the fault rupture zone of the 1999 Kocaeli earthquake (Fig. 5a) causing a 50-mm shear deformation in the elastomeric bearings and minor damage overall (Fig. 5b) (e.g., [61,62,26,53]). The No. 2 Overpass,

[1] A few additional cases of fault-crossing bridges damaged in past earthquakes have been reported in the literature, but are neither listed in Table 1 nor discussed in this section due to insufficient information or knowledge of the language in which the relevant references are published. This includes two fault-crossing bridges damaged during the recent 2016 M_w 7.0 Kumamoto, Japan, earthquake [109,90,118].